How an Underground Observatory Verified that Stars Shine by Nuclear Fusion and Suggested that Neutrinos May Oscillate

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Early Participants

Early participants: Shortly after the proposal by Davis and Bahcall in 1964 that a ^{37}Cl solar neutrino experiment was feasible, three of the people most involved were photographed in front of a small version of the chlorine tank. From right to left, they are: Raymond Davis, Jr., John Bahcall, and Don Harmer. (The photograph, courtesy of Raymond Davis, Jr., Appeared in Mercury, March/April 1990.)

The Inspection

Davis and Bahcall inspect the solar neutrino detector: Ray Davis (circa 1966) shows John Bahcall the tank containing 100,000 gallons of perchloroethylene, a neutrino observatory made of cleaning fluid. The picture was taken in the Homestake mine, shortly before the experiment began operating. The photograph is reproduced from J. N. Bahcall, "Solar Neutrinos," Proc. 2nd Int. Conference on High-Energy Physics and Nuclear Structure, 1967, pp. 232-255, ed. G. Alexander (North Holland, Amsterdam).

Nuclear Reaction Energy Budget

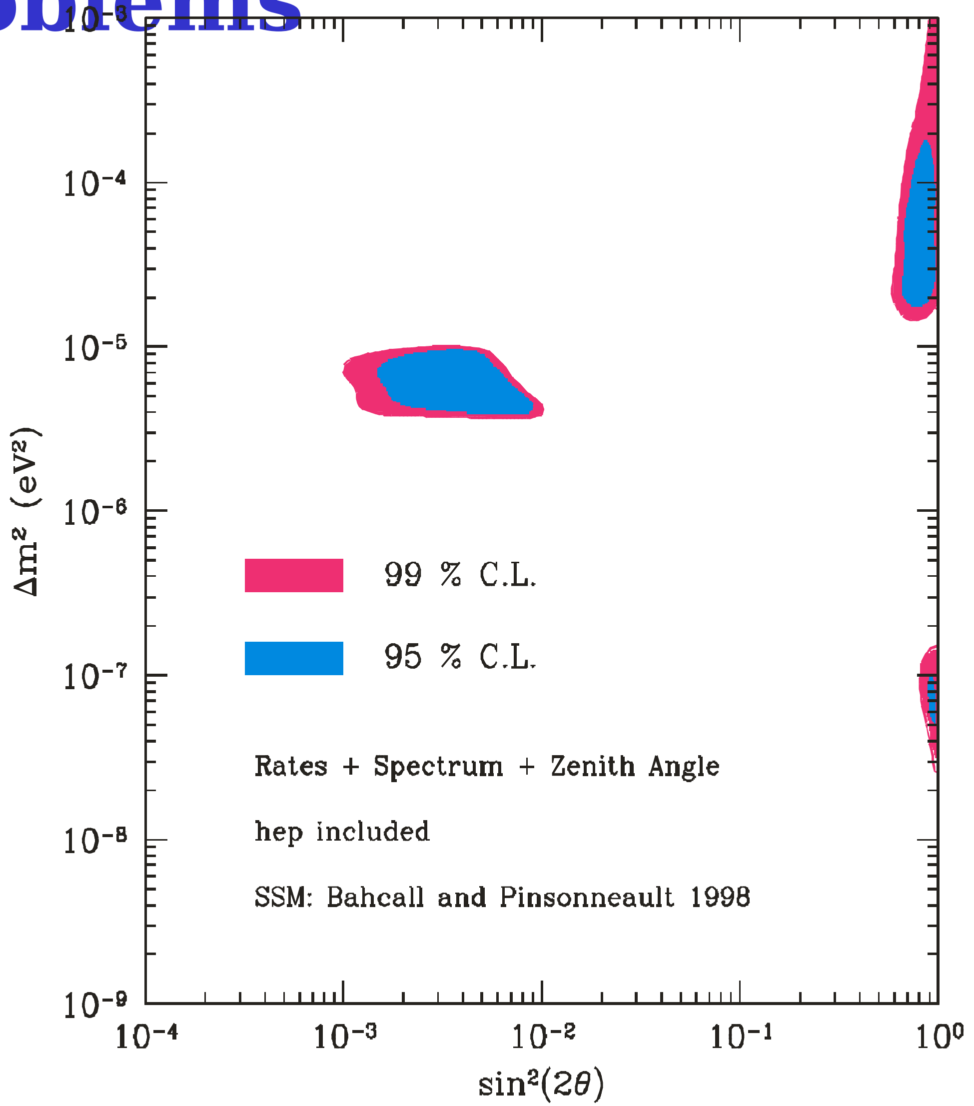
NUCLEAR BURNING

$$4p \longrightarrow {}^{4}\mathrm{He} + 2e^{+} + 2\nu_{e} + 25\ \mathrm{MeV}$$

Nuclear burning: The budget for the generic nuclear reaction that accounts for energy generation among main sequence stars consists of the burning of four protons to give an alpha particle, two positrons, and two neutrinos.

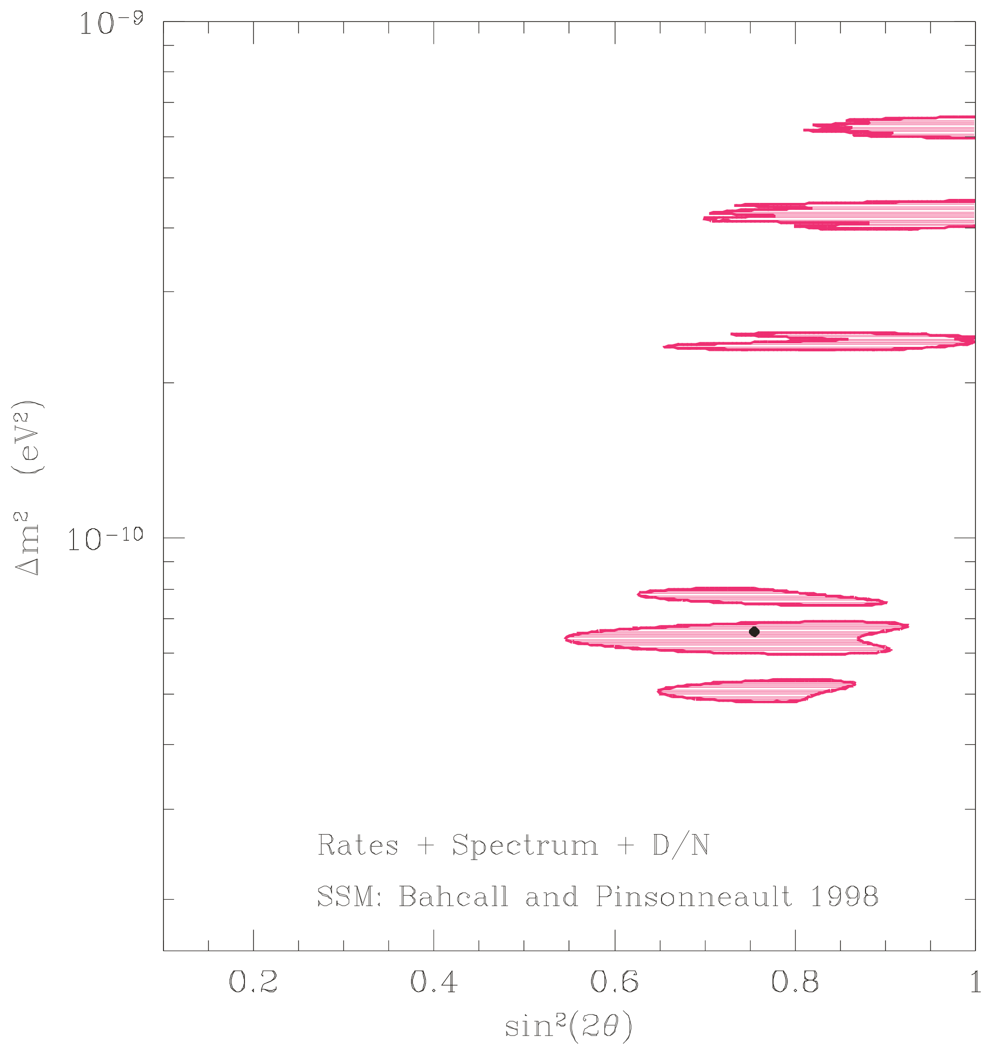
Neutrino Oscillations are the Favored Solution for Explaining the Solar Neutrino Problems

Neutrino oscillations in matter: The figure shows the regions in MSW parameter space that are consistent with the total rates observed in the four solar neutrino experiments (chlorine, Super-Kamiokande, GALLEX, and SAGE) and with the electron recoil energy spectrum and zenith angle distribution that are measured by Super-Kamiokande. The hep neutrino flux is allowed to vary freely. Contours are drawn at both 95% C.L. and 99% C.L. [Phys. Rev. D, 58, 096016-2 - 096016-22 (1998), hep-ph/9807216.]



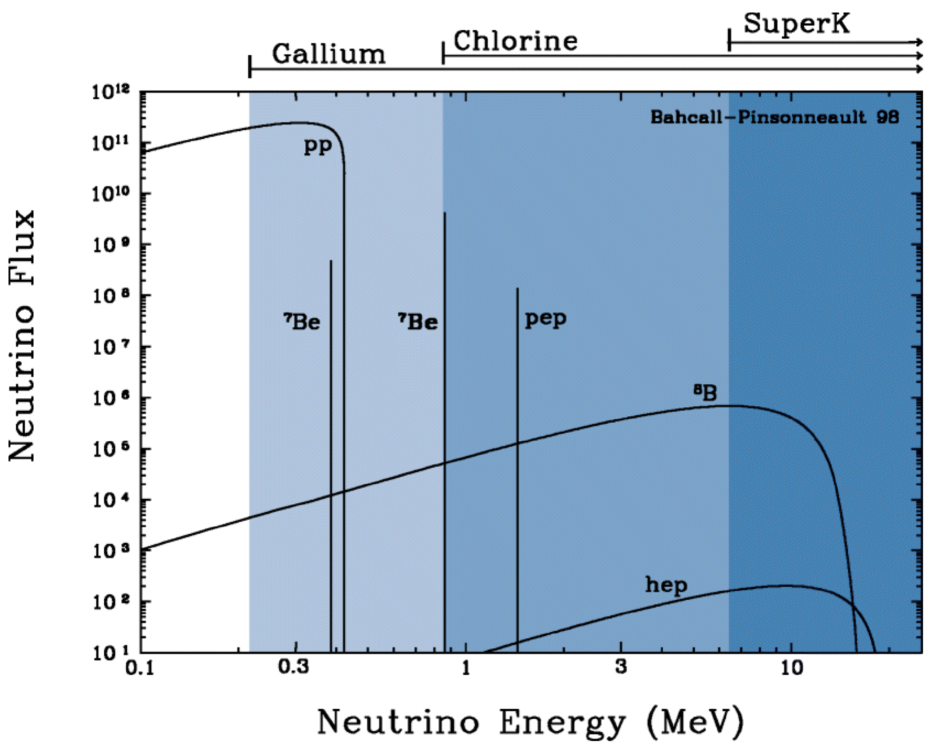
Neutrino Oscillations in Vacuum

The figure shows the allowed parameter region for vacuum oscillations that is consistent with the measured total rates, the recoil electron energy spectrum, and the Day-Night asymmetry. Contours are drawn at 99% C.L. [Ref. Phys. Rev. D, 58, 096016-2 - 096016-22 (1998), hep-ph/9807216.]



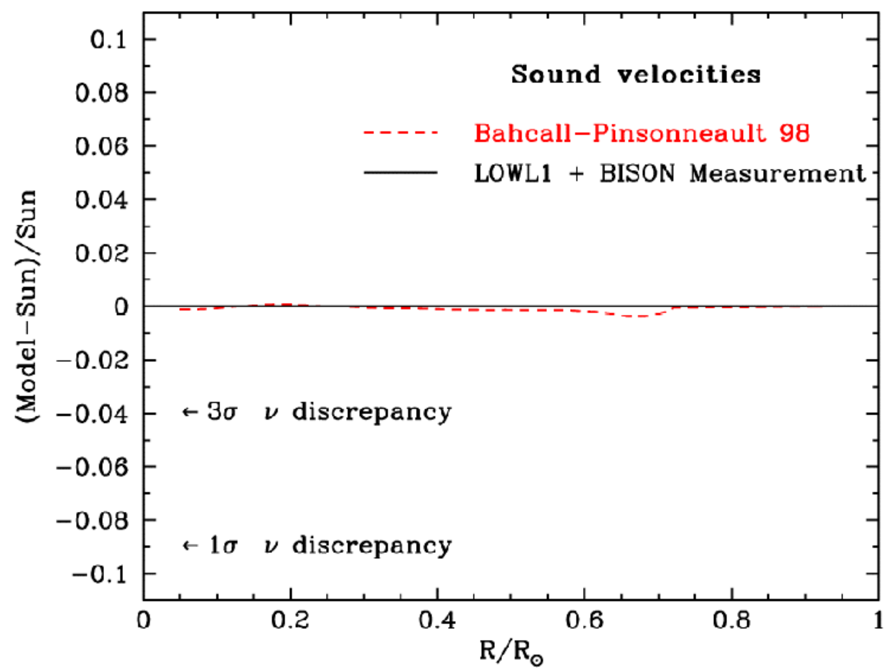
Solar Neutrino Energy Spectrum

The energy Spectrum of neutrinos from the pp chain of interactions in the Sun, as predicted by the standard solar model. Neutrino fluxes from sources (such as pp and ^8B) are given in the units of per cm^2 per second. The pp chain is responsible for more than 98% of the energy generation in the standard solar model. Neutrinos produced in the carbon-nitrogen-oxygen CNO chain are not important energetically and are difficult to detect experimentally. The arrows at the top of the figure indicate the energy thresholds for the ongoing neutrino experiments. [From the paper "Solar Neutrinos: Where We Are, Where We Are Going," ApJ 467, 475 (1996).]

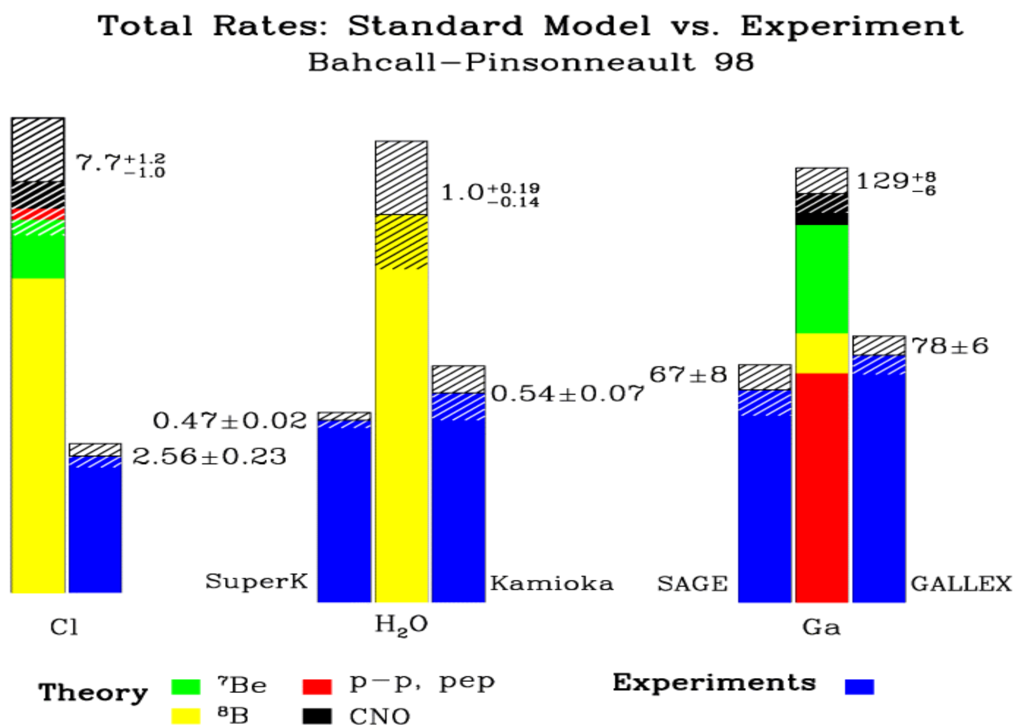


Helioseismology Confirms the Standard Solar Model

This figure shows the excellent agreement between the calculated solar model and the measured (Sun) sound speeds, a fractional difference of 0.001 rms for all speeds measured between 0.05 R and 0.95 R. There are no free parameters in the solar models. The figure shows the fractional difference between the predicted model sound speed and the measured solar values as a function of radial position in the sun (R is the solar radius). The vertical scale is chosen so as to emphasize that the fractional error is much smaller than generic fractional changes in the model, 0.03 to 0.08, that might significantly affect the solar neutrino predictions. This excellent agreement gives



Total Rates: Standard Model vs. Experiment



Predicted versus observed rates: The total rates in all five solar neutrino experiments are less than the rates predicted by the standard solar model.

http://www.sns.ias.edu/~jnb/SNviewgraphs/snviewgraphs.html